Release from informational masking in children: Effect of multiple signal bursts

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This study examined the degree to which increasing the number of signal presentations provides children with a release from informational masking. Listeners were younger children (5–7 years), older children (8–10 years), and adults. Detection thresholds were measured for a sequence of repeating 50-ms bursts of a 1000-Hz pure-tone signal embedded in a sequence of 10- and 50-ms bursts of a random-frequency, two-tone masker. Masker bursts were played at an overall level of 60-dB sound pressure level in each interval of a two-interval, forced choice adaptive procedure. Performance was examined for conditions with two, four, five, and six signal bursts. Regardless of the number of signal bursts, thresholds for most children were higher than thresholds for most adults. Despite developmental effects in informational masking, however, masked threshold decreased with additional signal bursts by a similar amount for younger children, older children, and adults. The magnitude of masking release for both groups of children and for adults was inconsistent with absolute energy detection. Instead, increasing the number of signal bursts appears to aid children in the perceptual segregation of the fixed-frequency signal from the random-frequency masker as has been previously reported for adults [Kidd, G., *et al.* (2003). J. Acoust. Soc. Am. **114**, 2835–2845]. © *2009 Acoustical Society of America.* [DOI: 10.1121/1.3087435]

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I. INTRODUCTION

A child's typical environment contains multiple sources of competing sounds. Each source generates acoustic waveforms consisting of individual frequency components that change over time. Many sound sources can be active at the same time and the child receives a mixture of overlapping waveforms from these multiple sources. In order to develop speech and language in this complex environment, the child must determine which frequency components were generated both sequentially and simultaneously from the same source. This process has been referred to in the literature as sound source segregation or sound source determination (e.g., Bregman, 1990; Yost, 1991).

Results from studies investigating children's speech perception in noise are consistent with the idea that the ability to perform sound source determination is immature during childhood. For example, children require a higher signal-to-noise ratio than adults to recognize speech in the presence of competing noise or speech maskers (e.g., Elliott *et al.*, 1979; Litovsky, 2005; Wightman and Kistler, 2005). Of particular interest to the study of sound source determination in children, these child-adult differences are pronounced for non-sensory or "perceptual" masking (Carhart *et al.*, 1969). Hall *et al.* (2002) observed larger developmental effects in speech recognition in the context of perceptual masking (i.e., spondee words presented in a two-talker masker) than in the context of "energetic" masking (i.e., words presented in speech-shaped noise). Note, however, that children's decreased performance on speech-in-noise tasks might also reflect their lack of experience using acoustic cues across different contexts. Moreover, the relation between sound source determination and auditory masking might be bidirectional for children. Increased masking might result in reduced sound source determination during childhood or vice versa.

Direct evidence supporting the hypothesis that infants and children have difficulty performing sound source determination is provided by studies of auditory stream segregation (Bregman, 1990). Auditory stream segregation refers to the ability to group incoming waveforms into separate auditory streams on the basis of acoustic cues that promote temporal coherence. For adults, these cues can include spatial separation, spectral separation, spectral profile, harmonicity, temporal onsets and offsets, and temporal modulations (e.g., Darwin and Carlyon, 1995; Yost, 1997). Results from several studies of auditory stream segregation during infancy indicate that this process is functional early in life (e.g., Winkler *et al.*, 2003) and that infants use many of the same acoustic cues that adults use to segregate auditory streams (Demany, 1982; Fassbender, 1993; McAdams and Bertoncini, 1997). Larger acoustic separations have been used for testing infants than for testing adults, however, and procedural modifications introduced to test infants limit direct comparisons with adult data. Thus, while the process of auditory stream segregation appears functional early in life, it is not clear how accurately this process operates as the child enters the preschool and school-aged years.

Recent data reported by Sussman *et al.* (2007) indicate that the ability to perform auditory stream segregation continues to develop well into childhood. School-aged children (5–11 years) and adults were presented with a sequence of

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alternating pure tones. The difference in frequency of the alternating tones was varied and listeners were asked to report whether they heard a single integrated auditory stream or two distinct streams. Compared to adults, children required a greater frequency difference between alternating tones before indicating they heard two separate streams. Sussman *et al.* (2007) suggested that the process of auditory stream segregation requires maturation and perceptual experience to fully develop.

We are unaware of other studies describing the efficiency and accuracy of sound source determination during childhood. Thus, it is not clear whether children's abilities to use cues in addition to frequency proximity also follow a prolonged course of development. This lack of information reflects, in part, how challenging it can be for young children to perform the conventional auditory streaming tasks. Interpreting data obtained from these studies is further complicated by the potential for differences in response bias across children and adults using conventional auditory streaming procedures. Differences in response bias can occur as a result of criterion placement and may be responsible for individual differences in the streaming percept across adult listeners for intermediate or ambiguous frequency separations (e.g., Rose and Moore, 1997). Furthermore, studies of complex auditory perception using single-interval tasks have reported developmental changes in response bias (e.g., Leibold and Werner, 2006). Thus, interpreting child-adult differences in auditory streaming is challenging. Observed developmental changes might reflect immaturity in auditory streaming mechanisms. Alternatively, these age effects might reflect differences in the underlying decision processes used by children and adults.

An alternative approach for examining the development of sound source determination is to examine whether children benefit from stimulus manipulations thought to aid in sound source determination by providing a release from "informational" masking (e.g., Watson *et al.*, 1975; Neff and Green, 1987; Kidd *et al.*, 1994). In this context, informational masking refers to masking produced by energy remote in frequency from the signal, that is, masking produced despite an adequate sensory-neural representation of the signal. For simultaneous masking of a pure-tone signal, these effects are largest when stimulus uncertainty is created by introducing random variations in the spectral content of a multi-tonal masker. For example, adults' thresholds for a fixed-frequency, pure-tone signal can be elevated by as much as 50 dB when the spectral content of a multi-tonal masker is varied on each presentation (e.g., Neff and Green, 1987). One advantage of using this approach is that measures of masking release can be obtained efficiently by estimating thresholds using multiple-interval, forced-choice adaptive procedures not likely to be influenced by the placement of the listener's response criterion (e.g., Marshall and Jesteadt, 1986).

The mechanisms responsible for informational masking are not fully understood, but a failure of sound source determination appears to be responsible for a substantial portion of the masking observed in these conditions (e.g., Kidd *et al.*, 1994, 2002; Neff, 1995; Durlach *et al.*, 2003). Evidence supporting this hypothesis is provided by studies that have manipulated stimulus properties thought to promote sound source determination, including spatial separation, asynchronous temporal onsets, and dissimilar temporal modulations (e.g., Darwin and Carlyon, 1995; Yost, 1997). A substantial release from informational masking is observed for most adult listeners when these cues are introduced (e.g., Kidd *et al.*, 1994; Neff, 1995; Oh and Lutfi, 1998; Arbogast *et al.*, 2002; Durlach *et al.*, 2003).

On average, children appear to be more susceptible to informational masking than adults (e.g., Allen and Wightman, 1995; Oh *et al.*, 2001; Wightman *et al.*, 2003). For example, Oh *et al.* (2001) found that the average threshold for detection of a 1000-Hz tone embedded in a random-frequency, multi-tonal masker was about 20 dB higher for children (4–16 years) than for adults. Given children's increased susceptibility to informational masking relative to adults and the mounting evidence that informational masking reflects difficulties performing sound source determination, identifying stimulus cues that benefit children's performance on these tasks has the potential to provide valuable information regarding the development of sound source determination. This approach has been used to examine whether informational masking in children can be reduced by presenting the signal and the masker to different ears (Wightman *et al.*, 2003; Hall *et al.*, 2005), asynchronous temporal onsets (Hall *et al.*, 2005; Leibold and Neff, 2007), spectro-temporal coherence (Hall *et al.*, 2005), spatial separation (Litovsky, 2005), and auditory-visual integration (Wightman *et al.*, 2006). As Hall *et al.* (2005) discussed, results from these studies suggest that the extent to which children benefit from stimulus cues that promote sound source determination for adults depends on the specific cue manipulated. For example, a smaller release from informational masking has been observed for children than for adults when the target signal and the masker are presented dichotically (Wightman *et al.*, 2003; Hall *et al.*, 2005). Both Wightman *et al.* (2003) and Hall *et al.* (2005) found that children receive limited benefit when a fixed-frequency pure-tone signal and a random-frequency multi-tonal masker are presented to opposite ears, a manipulation associated with a large masking release for adults. In contrast, informational masking can be effectively reduced for most children when the onset of a pure-tone signal is delayed relative to the onset of a multi-tonal masker. Children and adults receive a similar average masking release for signal-masker onset asynchronies of 120 ms (Hall *et al.*, 2005) or 100 ms (Leibold and Neff, 2007). Thus, whereas most children demonstrate substantial benefit for a temporal onset asynchrony cue, they demonstrate reduced efficiency for other stimulus cues such as contralateral presentation of the signal and masker. Discrepancies across studies indicate that the relative benefit or salience of stimulus cues that promote a release from informational masking changes with development. However, data remain limited and the benefit provided by several cues shown to aid adults' performance has not yet been determined for children. In addition, most developmental studies have examined performance across conditions with relatively large acoustic differences. Few developmental studies have parametrically varied the strength of the grouping cue or examined the extent to which children benefit from smaller manipulations.

This study examined the degree to which children benefit from a potential spectro-temporal grouping cue, multiple presentations of a constant-frequency, pure-tone signal. A modified "multiple-burst different" informational masking paradigm (Kidd *et al.*, 1994) was used to parametrically examine child-adult differences in informational masking release for conditions with two, four, five, and six bursts of a 50-ms, 1000-Hz tone embedded in a sequence of random-frequency, two-tone masker bursts. Multiple presentations of the fixed-frequency signal bursts appear to contrast with the random-frequency masker bursts to form a coherent auditory stream and reduce masking for adults (Kidd *et al.*, 2003; Huang and Richards, 2006). Children, however, appear to listen less selectively than adults in complex listening conditions (e.g., Lutfi *et al.*, 2003) and may require more signal presentations than adults to form a coherent stream and perceptually segregate the signal from the masker.

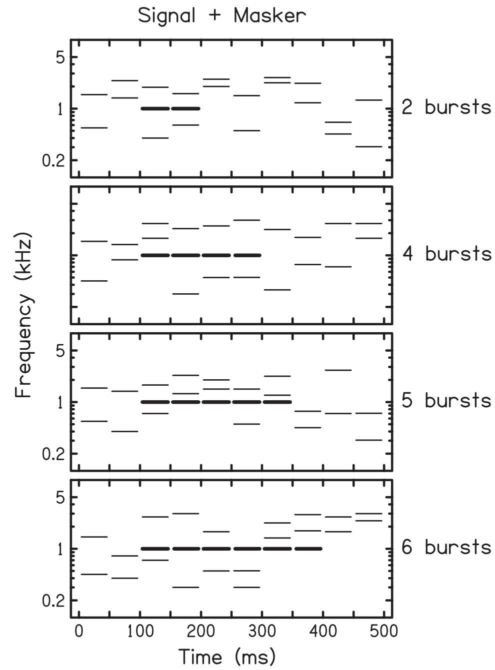

FIG. 1. Schematic representations of the stimuli and conditions are shown as spectrograms. The signal interval of a 2IFC trial with two, four, five, or six bursts of a 1000-Hz tone (bold) are illustrated. For all conditions, the masker consisted of ten bursts of two-component random-frequency maskers (light shading).

II. METHODS

A. Listeners

Fifteen children (5–10 years) and eight adults (20–29 years) participated in all conditions. Two groups of children were studied: (1) seven younger children aged 5–7 years and (2) eight older children aged 8–10 years. Younger children had a mean age (years:months) of 6:6 (range=5:5–7:6), older children had a mean age of 9:5 (range=8:6–10:5), and adults had a mean age of 24:1 (range=20:0–29:5). Listeners were required to pass a hearing screening prior to testing (re: ANSI, 1996) and had no known history of chronic ear disease. Testing occurred in a single-walled, sound-treated room. Adults and older children completed testing in a 2-h visit. Younger children were typically tested in two 1-h visits. Regular breaks were provided during testing, after the completion of two to three conditions for children and between blocks for adults. Three additional children were tested, but were excluded from data analysis. One child (age 5) did not meet the training criteria, discussed below. A second child (age 5) adapted out of bounds for one condition and did not provide sufficient data to estimate a threshold. Data for a third child (age 7) were excluded because of unusually variable threshold estimates across test sessions. A closer examination of this child's adaptive tracks revealed inconsistent responses and high variability (>5 dB) of reversals.

B. Stimuli and conditions

Following the multiple-burst paradigm of Kidd *et al.* (1994), the masker was a sequence of 10- and 50-ms tone bursts (5-ms, $\cos^2$, rise/fall ramps). There was no temporal overlap between successive masker bursts, resulting in a total duration of 500 ms for each masker sample. Individual masker bursts within the sequence were comprised of two frequency components drawn randomly from a uniform distribution with a range of 300–3000 Hz, excluding 920–1080 Hz. The frequency range from 920 to 1080 Hz extends beyond the equivalent rectangular bandwidth centered on 1000 Hz (Glasberg and Moore, 1990) and was excluded to reduce energy-based masking. The overall level of each burst was 60-dB sound pressure level (SPL) (57 dB/component).

The signal was a sequence of 50-ms bursts of a 1000-Hz tone (5-ms, $\cos^2$, rise/fall ramps). Across conditions, the number of signal bursts was varied. Performance for conditions with two, four, five, and six bursts was examined in the presence of the sequential masker. The choice of conditions was based on data reported by Kidd *et al.* (2003) for trained adult listeners using similar conditions as well as pilot data collected from untrained adult and child listeners using the current stimuli. Performance was not assessed for a one-burst condition in the present study. This condition was not tested because both the data reported by Kidd *et al.* (2003) and the pilot data indicated that most children and some adults had difficulty detecting a single, 50-ms burst of the 1000-Hz tone presented in a random, multiple-burst masker. The signal bursts were turned on and off synchronously with the masker bursts, but the onset of the initial signal burst was delayed by 100 ms relative to the first masker burst. Thus, the onset of the first signal burst coincided with the onset of the third masker burst. In addition, a minimum of two masker bursts were played following the offset of the signal bursts. The expectation was that the 100-ms asynchronous onset and offset between the signal and masker bursts would aid in the perceptual segregation of the signal from the masker to a similar degree for both adults and children (Hall *et al.*, 2005; Leibold and Neff, 2007). Schematic representations of the stimuli for the signal-plus-masker interval of one two-interval, forced choice (2IFC) trial are provided in Fig. 1. Thresholds were also measured for the two-burst and six-burst signals in quiet.

Stimuli were played through a 24-bit digital-to-analog converter (Digital Audio Laboratories) at a sampling rate of 20 kHz. Stimuli were presented monaurally to the listener's left ear via Sennheiser HD-25 earphones. Twenty-five masker sequences were generated and stored. The computer randomly selected a different masker sample from this file on each presentation. The same 25 masker samples were used for all masker conditions.

C. Procedure

Prior to testing, listeners completed training for the two-burst signal presented in quiet and both the two-burst and six-burst signals embedded in the random masker sequence. Children sat in front of a computer monitor. Using a two-interval, forced-choice procedure, each trial consisted of two successive observation intervals (indicated by "1" and "2" on the computer monitor). The interstimulus interval was 500 ms. The signal was presented at a clearly audible level during training, based on pilot data. The initial training level was 80-dB SPL. The training level was increased to 90-dB SPL for children who had difficulty performing the task at the initial level. The signal occurred in either interval with equal *a priori* probability and children were instructed to verbally indicate which interval contained the signal. An experimenter sat inside the booth with the child, initiated trials, and entered responses. Correct responses were rewarded by an image presented on the monitor in a video game format. Adults were tested using the same procedure, but were alone in the booth, self-initiated trials, and entered responses directly. Training continued until the listener correctly responded to a minimum of four correct responses within five consecutive trials. As noted previously, one child (age 5) was unable to meet the training criteria.

Following training, thresholds for the 1000-Hz signal were measured with the two-interval, forced-choice procedure used for training, but combined with a two-down, one-up adaptive paradigm that estimated 70.7% correct on the psychometric function (Levitt, 1971). For the first testing block, the individual training level was used as the starting level of the adaptive track. For the second and subsequent testing blocks, the starting level was 10–15 dB above the initial threshold estimate, adjusted for individual listeners. The initial step size was 4 dB, followed by a step size of 2 dB starting with the third reversal. The maximum allowable signal level was 96-dB SPL. For masked conditions, the adaptive track was terminated after 12 reversals and threshold was determined by averaging the levels for the last 10 reversals. For quiet conditions, the adaptive track was terminated after eight reversals and threshold was determined by averaging the levels for the last six reversals.

The order of testing was randomized across all conditions within blocks for each listener. All listeners completed two blocks of testing. Additional blocks were completed if the first two threshold estimates varied by more than 5 dB. For younger children, additional blocks were run for 36% of quiet conditions and 54% of random two-tone conditions. For older children, additional blocks were run for 19% of quiet conditions and 50% of random two-tone conditions. For adults, additional blocks were run for 6% of quiet conditions and 44% of random two-tone conditions. The two threshold estimates with the best agreement were used to determine a listener's average threshold for each condition.

III. RESULTS

Individual threshold estimates for the two-burst and six-burst signals presented in quiet are provided in Table I. Figure 2 shows average quiet thresholds for younger children (open triangles), older children (open squares), and adults (filled circles) as a function of the number of signal bursts (2 versus 6). Error bars represent ± 1 standard error (SE) of the mean threshold across listeners within each age group. For both groups of children, the average threshold for the six-burst signal in quiet is about 2 dB lower than the average threshold for the two-burst signal in quiet. The average adult threshold for the six-burst signal in quiet is about 4 dB lower than the average adult threshold for the two-burst signal in quiet.

A repeated-measures analysis of variance (ANOVA) of threshold was consistent with the trends observed in Fig. 2. No significant differences in absolute threshold across the three age groups were observed [$F(2,20)=2.1$; $p=0.1$], indicating similar performance in quiet for younger children, older children, and adults. However, this analysis showed a significant effect of number of signal bursts [$F(1,20)=9.1$; $p=0.007$], indicating thresholds in quiet decreased as the number of signal bursts increased from 2 to 6. There was no interaction between age group and number of signal bursts ($p=0.7$). Thus, increasing the number of signal bursts in quiet did not affect adults' performance to a significantly greater degree than it affected children's performance.

Individual thresholds for bursts of the 1000-Hz signal presented in the multiple-burst masker are also provided in Table I. Figure 3 shows average masked threshold for younger children (open triangles), older children (open squares), and adults (filled circles) as function of the number of signal bursts. Error bars represent ± 1 SE of the mean threshold across listeners within each age group. For all conditions, average masked threshold for both groups of children was higher than the average masked threshold for adults. Moreover, average masked thresholds for younger children were consistently higher than average masked thresholds for older children.

Despite age differences in susceptibility to masking, masked threshold decreased as the number of signal bursts increased for all three age groups. The largest improvement in average masked threshold was observed as the number of signal bursts increased from 2 to 4. The average threshold improvement in the four-burst condition relative to the two-burst condition was 15.6 dB (SE=7.3) for younger children, 14.2 dB (SE=3.5) for older children, and 9.5 dB (SE=1.3) for adults. A smaller, but progressive, improvement in threshold was observed as the number of signal bursts increased from 4 to 6. The average threshold improvement in the six-burst condition relative to the four-burst condition was 8.7 dB (SE=1.7) for younger children, 7.8 dB (SE=2.7) for older children, and 5.3 dB (SE=2.7) for adults.

TABLE I. Thresholds in decibel SPL for younger children (5–7 years), older children (8–10 years), and adults for the signal bursts presented in quiet and presented in the random masker sequence. The age of each listener is given in years:months.

	Quiet		Masker				
	2	6	2	4	5	6	Age
			Younger children				
YC1	12.5	26.3	90.6	83.4	72.0	73.9	5:5
YC3	8.4	3.1	76.8	52.9	57.4	40.0	5:10
YC3	13.4	8.4	87.2	82.6	90.7	76.4	6:1
YC4	8.8	4.8	72.9	70.9	62.6	64.4	6:11
YC5	4.8	2.7	90.0	82.1	71.5	68.6	7:2
YC6	15.3	7.3	89.9	82.6	72.0	71.1	7:4
YC7	10.0	7.1	83.9	27.7	28.8	26.9	7:6
Mean	10.5	8.5	84.5	68.9	65.0	60.2	
SE	1.3	3.1	2.7	8.0	7.2	7.2	
			Older children				
OC1	7.4	5.1	35.8	18.7	18.5	22.8	8:6
OC2	3.5	1.9	74.3	54.4	43.6	40.5	8:9
OC3	10.6	8.8	78.5	73.8	70.4	68.7	9:6
OC4	8.6	1.7	73.6	65.8	53.7	51.6	9:9
OC5	1.2	0.6	45.7	22.6	15.4	15.7	10:2
OC6	10.8	9.6	73.3	67.3	66.3	69.0	10:4
OC7	2.7	0.3	75.2	44.9	35.3	30.1	10:5
OC8	6.0	3.3	75.1	70.7	78.1	57.6	10:5
Mean	6.3	3.9	66.4	52.3	47.7	44.5	
SE	1.3	1.3	5.7	7.7	8.3	7.2	
			Adults				
A1	4.5	2.8	25.7	17.6	16.8	18.0	20
A2	2.5	−2.3	37.6	21.2	15.6	10.0	20
A3	16.6	14.6	34.8	27.4	27.6	25.1	20
A4	2.5	0.7	76.2	64.7	56.1	60.7	21
A5	10.3	3.4	66.0	54.0	39.0	32.8	26
A6	9.6	5.1	30.4	22.2	20.1	16.9	27
A7	7.3	1.0	62.7	55.1	60.3	58.7	27
A8	6.5	4.5	70.3	65.2	60.3	62.7	29
Mean	7.5	3.7	50.5	40.9	37.0	35.6	
SE	1.7	1.8	7.2	7.3	6.9	7.7	

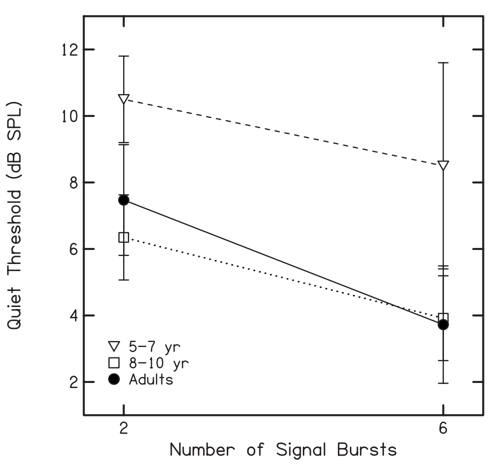

FIG. 2. Average quiet thresholds across listeners (with SEs) for each of the three age groups (open triangles for younger children, open squares for older children, and filled circles for adults) are presented for the two-burst and six-burst signals.

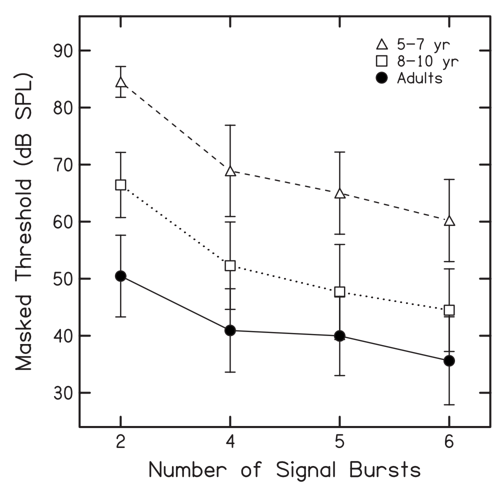

FIG. 3. Average masked thresholds across listeners (with SEs) for each of the three age groups (open triangles for younger children, open squares for older children, and filled circles for adults) are presented for the two-, four-, five-, and six-burst signals.

A repeated-measures ANOVA of threshold was performed with one between-subjects factor (age) and one within-subjects factor (number of signal bursts) to assess developmental effects in the amount of masking release associated with increasing the number of signal bursts. This analysis revealed a significant main effect of number of bursts [$F(3,60)=32.9$; $p<0.001$], indicating thresholds decreased as the number of bursts of the 1000-Hz signal increased. *Post hoc* pairwise comparisons (Bonferroni, using a criterion of $p<0.05$) indicated that thresholds were significantly higher in the two-burst condition than in the four-, five-, and six-burst conditions. Thresholds were also higher in the four-burst condition than in the six-burst condition. Thresholds were not significantly different across the four-burst and five-burst conditions ($p=0.06$) or across the five-burst and six-burst conditions ($p=0.2$). The main effect of age was also significant [$F(2,20)=4,4$; $p=0.03$], indicating developmental effects in susceptibility to masking for these conditions. *Post hoc* pairwise comparisons (Bonferroni, using a criterion of $p<0.05$) indicated that thresholds were significantly higher for younger children than for adults, but were not significantly different across older children and adults ($p=0.7$) or across older and younger children ($p=0.3$). No interaction between number of bursts and age was observed [$F(6,60)=0.6$; $p=0.7$], indicating that threshold decreased with increased signal bursts in a similar way for younger children, older children, and adults.

Considerable between-subjects variability in both amount of masking and masking release was observed for all three age groups, as shown by the error bars in Fig. 3 and the individual thresholds provided in Table I. Despite large individual differences between and within age groups, however, thresholds for all listeners decreased as the number of signal bursts increased. With the exception of one younger child, all listeners showed a masking release of 4 dB or greater as the number of signal bursts was increased from 2 to 4. The remaining listener (age 6:11) showed a masking release of 2 dB. All listeners, including the younger child (6:11) who showed a 2-dB improvement in threshold when the number of signal bursts increased from 2 to 4, showed a masking release as the number of signal bursts was increased from 2 to 6. Also note that the majority of listeners showed additional masking release as the number of signal bursts was increased from four to six bursts.

IV. DISCUSSION

A. Child-adult differences in susceptibility to informational masking

1. Group differences

The current results support the hypothesis that informational masking is greater for children than for adults. Thresholds for the detection of bursts of a 1000-Hz signal in the presence of a random-frequency masker sequence were elevated for all three age groups. However, younger children had significantly higher masked thresholds than adults. These results are in agreement with previous developmental studies of informational masking that have employed sequential multi-tonal maskers (Hall *et al.*, 2005), simultaneous multi-tonal maskers (e.g., Oh *et al.*, 2001; Wightman *et al.*, 2003), and speech maskers (e.g., Wightman and Kistler, 2005). The mechanisms responsible for these age-related changes in susceptibility to informational masking are not fully understood, but are not likely the consequence of immature sensory processing [reviewed by Werner (1996)]. Instead, children's increased susceptibility to informational masking appears to reflect developmental changes in nonsensory processes. For example, Lutfi *et al.* (2003) modeled children's responses in a pure-tone informational masking task, and their elevated thresholds suggest a reduced ability to attend selectively to the auditory filter containing the signal.

2. Individual differences

As in previous investigations of informational masking involving both children (e.g., Oh *et al.*, 2001) and adults (e.g., Neff and Dethlefs, 1995), a wide range of performance was observed within and across age groups. However, systematic differences in threshold variability were not observed across the three age groups. For example, the range of masked thresholds for the six-burst condition spanned a range of 47 dB for younger children and 53 dB for both older children and adults. In contrast, Hall *et al.* (2005) observed a smaller range of thresholds for adults (30 dB) than for children aged 4–9 years (50 dB) for an eight-burst signal embedded in a sequence of two-tone masker bursts with random spectra. Differences in methodology across studies make it difficult to determine the basis for this discrepancy. Note, however, that differences in threshold variability between the current data and Hall *et al.* (2005) reflect an increased range of threshold estimates for adults in the current study. A comparison of threshold estimates for children across the two studies indicates a similar range of performance.

B. Child-adult similarity in release from informational masking

The main purpose of this study was to determine whether there are developmental effects in informational masking release as the number of signal presentations increased. The results indicate this cue reduced masking for younger children (5–7 years), older children (8–10 years), and adults. Even with adults' lower thresholds in the baseline (two-burst) condition compared to younger children, the three age groups experienced similar release from masking as the number of signal bursts increased.

The pattern of results for untrained adult listeners in the current study is in general agreement with the pattern observed by Kidd *et al.* (2003) for trained adults. This agreement suggests that increasing the number of presentations of the signal, as opposed to the masker, is likely responsible for reducing informational masking using the multiple-burst different paradigm. Kidd *et al.* (2003) examined listeners' ability to detect a sequence of 60-ms, 1000-Hz signal bursts embedded in a masker consisting of 60-ms bursts of a random-frequency, eight-tone complex. In contrast to the current study in which the number of masker bursts was 10 for all conditions, Kidd *et al.* (2003) varied the number of masker bursts across conditions to match the number of signal bursts. In conditions with one, two, four, and eight bursts and an inter-burst interval of 0 ms, all listeners showed a masking release as the number of signal and masker bursts was increased. The current results corroborate these previous findings by confirming the effectiveness of providing listeners with a coherent signal across time for reducing informational masking (e.g., Kidd *et al.*, 2003; Huang and Richards, 2006). Inconsistent with the result of Kidd *et al.* (2003), however, the present study showed smaller reductions in threshold as the number of signal bursts increased. Whereas Kidd *et al.* (2003) found an average masking release of 24 dB as the number of masker bursts was increased from 2 to 4, an average masking release of 10 dB was observed here. Differences in stimuli are the most likely reason for this discrepancy. In addition to varying the number of both signal and masker bursts, Kidd *et al.* (2003) used masker bursts comprised of eight pure-tone components. Maskers with fewer components, such as the two-component maskers used in the current study, have been shown to produce less informational masking (e.g., Neff and Green, 1987) and thus, a reduced potential for masking release.

Increasing the number of presentations of a 1000-Hz signal was clearly an effective cue for children as well as adults. Despite considerable individual differences, children as young as 5 years of age were able to take advantage of the increased number of signal bursts. Though a direct comparison is not evident in the literature, Hall *et al.* (2005) also found that most children (5–10 years) benefited from stimulus cues believed to be related to spectro-temporal coherence. Inconsistent with the current results, however, Hall *et al.* (2005) observed a smaller average masking release for children than for adults. Perhaps the most important difference across the two studies is that Hall *et al.* (2005) assessed informational masking release related to manipulations made to the spectral properties of the masker. The current study examined informational masking release related to changes made to the temporal properties of the signal.

C. Relation between susceptibility to and release from informational masking

The finding that children's thresholds were generally higher than adults in the baseline (two-burst) condition complicates the interpretation of age differences in masking release. Increased susceptibility to informational masking in some children may have permitted larger reductions in threshold. Several observations are inconsistent with this explanation. First, children with the greatest release from masking did not have uniformly high thresholds in the baseline (two-burst) condition. In fact, the child (8:6) with the lowest threshold for the two-burst condition among all children showed a larger-than-average masking release (17 dB) as the number of signal bursts increased to four bursts. Second, regression analyses indicated that thresholds in the two-burst condition were not a significant predictor of the amount of masking release observed as the number of signal bursts was increased from two to four bursts for any age group (all p's >0.8). Third, a comparison of informational masking release among adults found no evidence of differences in masking release for the four adults with the lowest two-burst thresholds ($<$40-dB SPL) versus the four adults with the highest two-burst thresholds ($>$60-dB SPL). The average masking release for the four adults with the lowest thresholds was 10 dB. Similarly, the average masking release for the four adults with the highest thresholds was 9 dB. Together, these observations are inconsistent with the viewpoint that developmental effects in susceptibility to informational masking are responsible for the amount of benefit provided by increasing the number of signal presentations.

The average child-adult difference in threshold for the six-burst signal embedded in the random masker was 26 dB for younger children and 9 dB for older children. Thus, children's thresholds remain elevated compared to adults despite their ability to benefit from the increased number of signal bursts. The basis for children's increased susceptibility to informational masking relative to adults in the presence of an effective cue is unknown. However, this finding is consistent with previous studies that have examined developmental effects in susceptibility to and release from informational masking. For example, Leibold and Neff (2007) observed a similar effect of reducing masker-spectral variability and adding an onset/offset asynchrony cue for children and adults in the context of a simultaneous informational masking task. Nonetheless, Leibold and Neff (2007) reported that children's thresholds remained elevated compared to adults for conditions in which both of these grouping cues were available.

D. Energy detection versus perceptual segregation

One explanation for the observed masking release is that listeners combined or integrated stimulus energy across time to improve performance. It has been well documented that detection thresholds for a pure-tone signal presented in quiet or in broadband noise decrease as signal duration increases from about 10 to 200–300 ms [reviewed by Gerken *et al.* (1990)]. This phenomenon is typically referred to as temporal integration. Several models have been proposed to account for temporal integration, including models that assume that listeners integrate stimulus energy across 200–300 ms (e.g., Swets *et al.*, 1959; McKinley and Weber, 1994) and more recent models that assume that the listener's decision is based on information combined across multiple shorter "looks" or samples (Viemeister and Wakefield, 1991).

The current data for the signal presented in the random two-tone masker are inconsistent with energy-detector and multiple-looks models. For example, a decrease in threshold of approximately 10 dB/decade increase in signal duration is predicted using a simple energy-detector model that assumes linear integration. For the current stimuli, this prediction corresponds to an improvement in threshold of approximately 3 dB for the four-burst signal (200 ms) compared to the two-burst signal (100 ms). In contrast to the predicted improvement, the average observed masking releases were 16, 14, and 10 dB for younger children, older children, and adults, respectively. The discrepancy between predicted and observed performances for the random two-tone masker suggests that listeners are not basing their decisions on absolute energy detection. In addition, the average observed threshold improvement in quiet across the six-burst and two-burst signals was about 2 dB for both groups of children and 4 dB for adults. Thus, whereas the observed threshold improvement was equal to (adults) or slightly less than (children) predicted for optimal energy detection in quiet, the magnitude of threshold improvement for all three age groups with increasing signal bursts was considerably greater than predicted in the presence of the random two-tone masker.

Previous work by Kidd *et al.* (2003) examined whether a multiple-looks model (Viemeister and Wakefield, 1991) could account for adults' performance on multiple-burst different conditions. Both the number of signal bursts and the silent interval between successive bursts (interburst interval) were manipulated. Consistent with the multiple-looks model, masking decreased as the number of bursts increased. However, several observations were inconsistent with the multiple-looks model. First, the observed magnitude of masking release exceeded the amount predicted by the model. Second, masking increased as the interburst interval increased. Third, the group-mean slope of the psychometric function increased as the number of signal bursts increased or as the interburst interval decreased. A similar increase in the slope of the psychometric function with reductions in informational masking has been observed by researchers using a simultaneous multi-tonal paradigm (e.g., Durlach *et al.*, 2005). Based on these observations, Kidd *et al.* (2003) suggested that increasing the number of bursts of the fixed-frequency signal contrasted with the random-frequency masker to provide an effective perceptual grouping cue. The magnitude of masking release and the discrepancy across quiet and masked conditions observed in the current study suggest that increasing the number of signal bursts strengthens perceptual coherence and reduces thresholds for children as well as for adults.

V. CONCLUSIONS

The results of the current study indicate that multiple presentations of a constant-frequency signal embedded in a random-frequency masker provide both children and adults with a robust cue for reducing informational masking. Although younger children were more susceptible to informational masking than adults, a similar decline in thresholds was observed as the number of signal bursts was increased for all age groups. Determining the relative importance of stimulus cues that reduce informational masking has the potential to provide insight into the mechanisms responsible for children's increased susceptibility to auditory masking. Further studies are needed to determine which cues are the most salient during development, how children integrate multiple cues to improve performance in the presence of competing sounds, and whether infants and children can benefit from similar acoustic cues in more natural environments.

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